STUDIES OF HUMAN DYNAMIC SPACE ORIENTATION USING TECHNIQUES OF CONTROL THEORY

Third Semi-Annual Status Report on
NASA Grant NsG-577

June 1965

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I. INTRODUCTION

The Man-Vehicle Control Laboratory performs research in a number of areas relating to the limitations and capabilities of men involved in the guidance, control and stabilization of moving vehicles. Our approach stresses the application of automatic control theory to an interdisciplinary field which includes problems in psychology and biology as well as control systems. The design of experiments and analysis of results leans heavily on the concepts of analytic or semi-analytic models of human operator characteristics.

A schematic breakdown of the problem of human dynamic orientation is shown in Figure 1, where those items which are starred represent areas of concentrated effort during the first half of 1965. In addition to the areas of interest described in previous status reports, we have begun serious consideration of the human adaptive mechanism and the problems of adaptive control in combined man-machine systems. The following sections of this report will touch briefly on the areas of research carried out in each of the four problem subdivisions: sensors, control and compensation, motor mechanisms, and controlled vehicles.

II. SENSORS

Control Models for the Normal Vestibular System

One of the primary goals of the research carried out under subject grant has been a better understanding of the effect of motion on the ability of men to perform a variety of control actions. The otoliths and semi-circular canals making up the vestibular system in man required fuller exploration. Consequently, an extensive experimental and analytic study of the dynamic characteristics of these sensors was undertaken, using our two-axis angular motion simulator and one-axis linear motion simulator. Many of the results of this research are presented in the doctoral thesis of Jacob L. Meiry, which also appears as a Man-Vehicle Control Laboratory Technical Report under the subject grant. Dr. Meiry has been appointed an Assistant Professor in Aeronautics and Astronautics and Post-Doctoral Fellow in Engineering, and will remain with the laboratory to carry on this research program. The abstract of his thesis is given below.

"The Vestibular System and Human Dynamic Space Orientation"
by
Jacob L. Meiry

ABSTRACT

The motion sensors of the vestibular system are studied to determine their role in human dynamic space orientation and manual vehicle control. The investigation yielded

control models for the sensors, descriptions of the subsystems for eye stabilization, and demonstrations of the effects of motion cues on closed loop manual control.

Experiments on the abilities of subjects to perceive a variety of linear motions provided data on the dynamic characteristics of the otoliths, the linear motion sensors. Angular acceleration threshold measurements supplemented knowledge of the semicircular canals, the angular motion sensors. Mathematical models are presented to describe the known control characteristics of the vestibular sensors, relating subjective perception of motion to objective motion of a vehicle.

The vestibular system, the neck rotation proprioceptors and the visual system form part of the control system which maintains the eye stationary relative to a target or a reference. The contribution of each of these systems was identified through experiments involving head and body rotations about a vertical axis. Compensatory eye movements in response to neck rotation were demonstrated and their dynamic characteristics described by a lag-lead model. The eye motions attributable to neck rotations and vestibular stimulation obey superposition when both systems are active.

Human operator compensatory tracking is investigated in simple vehicle orientation control systems with stable and unstable controlled elements. Control of vehicle orientation to a reference is simulated in three modes: visual, motion and combined. Motion cues sensed by the vestibular system and through tactile sensation enable the operator to generate more lead compensation than in fixed base simulation with only visual input. The tracking performance of the human in an unstable control system near the limits of controllability is shown to depend heavily upon the rate information provided by the vestibular sensors.

Vestibular-Tactile Experiments with Labyrinthine Defective Subjects

The experiments described above were designed to explore vestibular system control functions by experimental isolation of the vestibular, tactile and visual input sources. An alternate approach in this investigation is the testing of subjects with known defects or complete absence of a functioning vestibular system, and comparing their experimental results with normals. A joint series of experiments to this end was suggested by Captain Ashton Graybiel, Director of Research of the U. S. Navy School of Aviation Medicine, Pensacola, Florida. Captain Graybiel made arrangements for himself and five other staff members to come to M.I.T. with eleven carefully selected test subjects for a week's testing in July. In preparation for these experiments, the linear acceleration cart was modified and overhauled to increase its frequency response and reduce external motion cues transmitted through vibration. A summary of the twelve experiments planned for the M.I.T.-U.S.N. Vestibular Series is given below:

<u>First goal</u>: Eye stabilization - role of the vestibular system in conjunction with visual and neck proprioceptive systems.

<u>Experiments</u>: Sinusoidal Rotational Stimuli-measurement of horizontal eye movements.

a) Vestibular nystagmus in dark - head and body rotate together 0.04 to 2.0 cps, 5 frequencies

b) Vestibular stimulation with <u>inside rotating</u> visual field

c) Vestibular stimulation with <u>external fixed</u> visual field

d) Neck rotation in dark - head fixed - six frequencies

e) Vestibular and neck rotation in darkness

f) Head and neck stationary, visual target motion

<u>Experiment</u>: Sinusoidal Linear Acceleration - measurement of horizontal eye movements, if any.

<u>Second goal</u>: Threshplds of the vestibular system compared with tactile acceleration thresholds.

<u>Experiments</u>:

a) Constant angular acceleration, head and body rotate together, measurement of time to subjective detection - 0.15 to 13 deg/sec^2 in 5 steps

b) Constant linear acceleration, upright position, 0.0075 to 0.2 g's in 5 steps

c) Phase of subjective velocity for sinusoidal linear accelerations 0.025 to 0.8 cps

<u>Third goal</u>: Role of the vestibular system in providing rate information for vehicle control.

<u>Experiments</u>:

a) Control with respect to the vertical of unstable system of varying difficulty - fixed base

b) Control of same system while seated in moving cab without visual display

III. CONTROL AND COMPENSATION

Adaptive Control

Several aspects of the characteristics of the human as an adaptive controller have been considered in an attempt to establish the principal types of adaptive control and to set forth the requirements for optimum man-machine adaptive control. Many of these ideas are summarized in a paper entitled "Adaptive Functions of Man in Vehicle Control Systems" by Y. T. Li, L. R. Young, and J. L. Meiry, prepared for presentation to the International Federation of Automatic Control (Teddington) Symposium on the Theory of Self-Adaptive Control Systems, September 14-17, 1965. An abstract of this paper is given below:

ABSTRACT

Inability of human pilots to introduce adequate adaptation of their control provided much of the motivation for the development of automatic adaptive control systems. The rapid change in vehicle system characteristics in high performance aircraft, which may climb from sea level to extreme high altitudes in minutes, required automatic adaptive control to relieve the burden on the operator.

This paper examines the principles and composition of existing automatic adaptive control systems and on these bases the human adaptive as well as primary control functions are analyzed.

In general, the human outshines the automatic system with his huge capacity for open loop or programmed control; but he lacks the capacity and speed for making on line computations needed in the operation of an active continuous adaptive system. Humans can also perform some passive type

of very simple active type adaptation, but would require the assistance of a computer to perform complicated active adaptation.

This limitation is responsible for the dominance of mechanized systems for adaptive control. There are advantages attributable to a computer-assisted human adaptive control system considering the huge capacity of man's open loop adaptation. Visual or some other form of multi-input display becomes a necessary medium when computer-man coupling is to be made effectively. Considering man's remarkable ability of pattern recognition this task may be in many cases easier than the coupling of a computer with an automatic actuator when a complicated function is to be recognized and manipulated.

Phase Plane Display

Investigations were continued on the possibilities of using a modified phase plane display for integrated presentation of error and error rate in piloted control of high order systems. It was verified that a simple phase plane display provided satisfactory information for control of a system consisting of three cascaded integrations, and permitted smoother, more accurate control than the simple compensatory error display with low order systems. The definition of "safe regions" in the phase plane leading to suboptimal conservative trajectories facilitated its use by naive subjects.

Contact Analog Display of Landing Strips

A simple contact analog display was required for use in several of the vehicle simulation programs under way in the laboratory, to simulate some aspects of the visual information a pilot would derive by looking out of his window. As a general tool to display three angles indicating attitude of the vehicle and three displacements indicating its position, a simple contact analog was developed to display on an oscilloscope the lights defining the side of the runway and an artificial horizon, which moved according to the perspective that would be seen from the vehicle. This display is controlled directly from the attitude and displacement information generated in the analog computer simulation of the particular vehicle under study, and serves as a general laboratory tool.

The Effect of a No-Protein Diet and Control Stick Variations on Manual Tracking

For some time we have experimented with an adaptive tracking task in which the controlled element dynamics adapt to the operator's ability to control. Such a task provides a rapid measure of the operator's overall control ability. This task was used as a test in conjunction with a pilot experiment by the Department of Nutrition and Food Science to determine the effect of a no-protein diet on human operators' tracking ability. The results are presented in an M.I.T. Man-Vehicle Control Laboratory Internal Memorandum entitled "A Study of the Effect of a No-Protein Diet and Control Stick Variations on Manual Tracking Performance for a System with Adaptive Unstable Dynamics, by Philip Kilpatrick and Laurence R. Young, April 15, 1965. The abstract of that memorandum is given below:

ABSTRACT

The purpose of this experiment was to study the effects of a no-protein diet on a human operator's ability to perform a difficult manual tracking task and to compare the merits of a linear, on-off, and pulse type of control stick.

The experiment was conducted in the M.I.T. Man-Vehicle Control Laboratory under N.A.S.A. grant NsG-577 in collaboration with the Nutrition and Food Science Department.

The test required the subjects to control an inherently unstable system. The level of system instability changed during each tracking run depending on subject performance. The instability increased if the subject held the displayed error below a criterion level and decreased if the subject made errors larger than the criterion. The system was designed to adjust automatically to the maximum level of difficulty the subject could control. This task may be visualized as similar to balancing a variable length inverted pendulum. The pendulum length became shorter, more difficult to balance, with good performance; and longer, less difficult to balance, with poor performance.

Presumably any adverse dietary effects on coordination or reaction time and performance differences between control sticks would be more evident when the subject was forced to operate at the limits of control.

The dietary effect was studied by comparing the performance of a control and diet group before and at the end of a five-day diet. Each group consisted of five M.I.T. undergraduates. During the testing period, the control group followed their normal daily routine while the diet group was kept under the supervision of the Nutrition and Food Science Department.

Performance was measured by computing the average level of instability attained during each run and the average control stick output necessary to control the system. A constant stick output applied a constant torque or angular acceleration to the unstable system.

Briefly, the results indicated minor dietary effects and that the linear controller was superior to the non-linear controller for this task.

IV. MOTOR MECHANISMS

Pulse, Bang-Bang and Continuous Control Sticks

In continuation of our consideration of the human operator as a bang-bang controller, we extended our investigations of various types of linear and non-linear control sticks. Although non-linear control sticks can assist in stabilization of certain very sluggish high order control systems, it is not clear that they are advantageous in all high order systems. In particular, in the comparative study performed in conjunction with the nutrition experiment mentioned above, where the task was control of an unstable pendulum, it was not possible to fina a single force level pulse or bang-bang control which would enable subjects to generate large forces needed to overcome large errors and at the same time allow him to exercise fine control about the zero error position. For this reason we are continuing our study of non-linear control stick characteristics which depend upon the magnitude of the error signal.

Postural Control as an Output Mechanism

The ability of men to generate fine balancing control by their postural reflex has led us to consider experiments in which the input to a vehicle control system comes from man's own balancing output rather than his manipulation of a control stick. An experimental apparatus has been constructed to be fitted into the two-axis angular motion simulator, permitting subjects to control the motion of the simulator by shifting their weight balance on a platform.

V. CONTROLLED VEHICLES

In an attempt to apply some of our research findings to practical problems of man-vehicle control, we have chosen several challenging and illustrative practical vehicle control problems for study and simulation. In each of these we have concentrated on the control characteristics required of the operator and the effect of motion as a secondary input to the man.

Flexible Booster Control

Control of a flexible booster vehicle by a man is a challenging task since the rigid body dynamics are unstable in the aerodynamic region and the higher frequency elastic modes tend to interfere with his ability to maintain stable control. A fixed and moving base simulation of control of a flexible booster is under way to establish the effects of the high and low frequency motion cues, the interaction between elastic mode amplitude and frequency and the ability to control the rigid body mode, and the duplication of control operator limitations in terms of display requirements and automatic stabilization necessary.

Man's Role in "Automatic" Blind Landings

The proposal of automatic blind landing systems for commercial air transportation has raised the question of the appropriate role of the pilot during the landing phase. In particular, the question of pilot adaptability in terms of backup or takeover in the event of system malfunction must be considered along with his ability to put in appropriate control responses to land the aircraft in zero-zero weather entirely on instrument information. Among the areas being investigated are the importance of motion cues in detecting malfunctions, the ability of the pilot to take over at any phase of the landing, and his ability to perform instrument landings starting from a variety of initial conditions.

Helicopter Control Characteristics

The control of the completely unstabilized helicopter is normally beyond the ability of the human operator, and consequently a number of passive or active stabilization loops are built into the vehicle. Since the vehicle is inherently a high order controlled element, it makes an interesting amplification of our hypothesis on the role of the vestibular system in control of high order systems. A systematic investigation is being planned on helicopter handling qualities, including the requirements on display, external stabilization, and the importance of motion cues.

VI. REPORTS AND PUBLICATIONS

The research carried out under NASA Grant NsG-577 has been reported in part in the following publications presented or prepared during the reporting period.

1. Li, Y.T., L.R. Young and J.L. Meiry, "Adaptive Functions of Man in Vehicle Control," IFAC (Teddington) Symposium, Sept. 1965.
2. Meiry, J.L., "The Vestibular System and Human Dynamic Space Orientation," M.I.T. Man-Vehicle Control Laboratory Report T-65-1, June 1965. (Also Sc.D. Thesis, M.I.T., 1965).
3. Young, L.R. and J.L. Meiry, "Bang-bang Aspects of Manual Control in High Order Systems," IEEE Transactions on Automatic Control, July 1965. (Also presented at the 1965 Joint Automatic Control Conference).
4. Meiry, J.L., "A Model for Otolith and its Implication on Human Spatial Orientation," International Astronautical Federation, Athens, Greece, Sept. 1965.
5. Young, L.R. and J.L. Meiry, "Manual Control of an Unstable System with Visual and Motion Cues," IEEE International Convention Record 13, Part 6, 1965 (Presented at IEEE International Convention, New York, March 1965 - one more section to come).

VII. PLANS, PROGRAMS AND PERSONNEL

Our plans for research in the latter half of 1965 call for continuation of the programs already in progress and described in this report, and initiation of three new areas mentioned in our proposal. The new areas are the following:

i) Fluid dynamics of the vestibular system and reactions to bizarre stimulation. Whereas the work we have done thus far has concentrated on the input-output characteristics of the semi-circular canals and otoliths, this study will investigate the actual mechanical events taking place in the labyrinth. We feel that some of the conventional explanations of "Coriolis stimulation" and caloric stimulation may prove misleading.

ii) An investigation of the identification of time varying systems - both as it applies to human identification of varying vehicle characteristics and automatic identification of human adaptive behavior.

iii) Study of the potential and limitations of manual control using audio input signals including study of the sensors (thresholds, dynamic response, habituation) for monaural and binaural listening to changes in pitch and intensity. Several vehicle systems applications will be studied, and digital coding of audio signals will be considered.

Each of these programs is expected to form the research area for three doctoral candidates who have recently joined the laboratory. In addition, at least five other graduate students and two undergraduates will be involved in various aspects of the research.

To meet the increasingly severe requirements of display, simulation and data reduction, as well as to fulfill the special laboratory needs in real time man-vehicle adaptive control, we have considered a number of analog and digital computers and conversion equipment. It was decided to purchase a self-contained hybrid computer system to tie into the two-axis angular motion simulator and the linear acceleration cart. This system is expected to be in operation by the end of 1965.

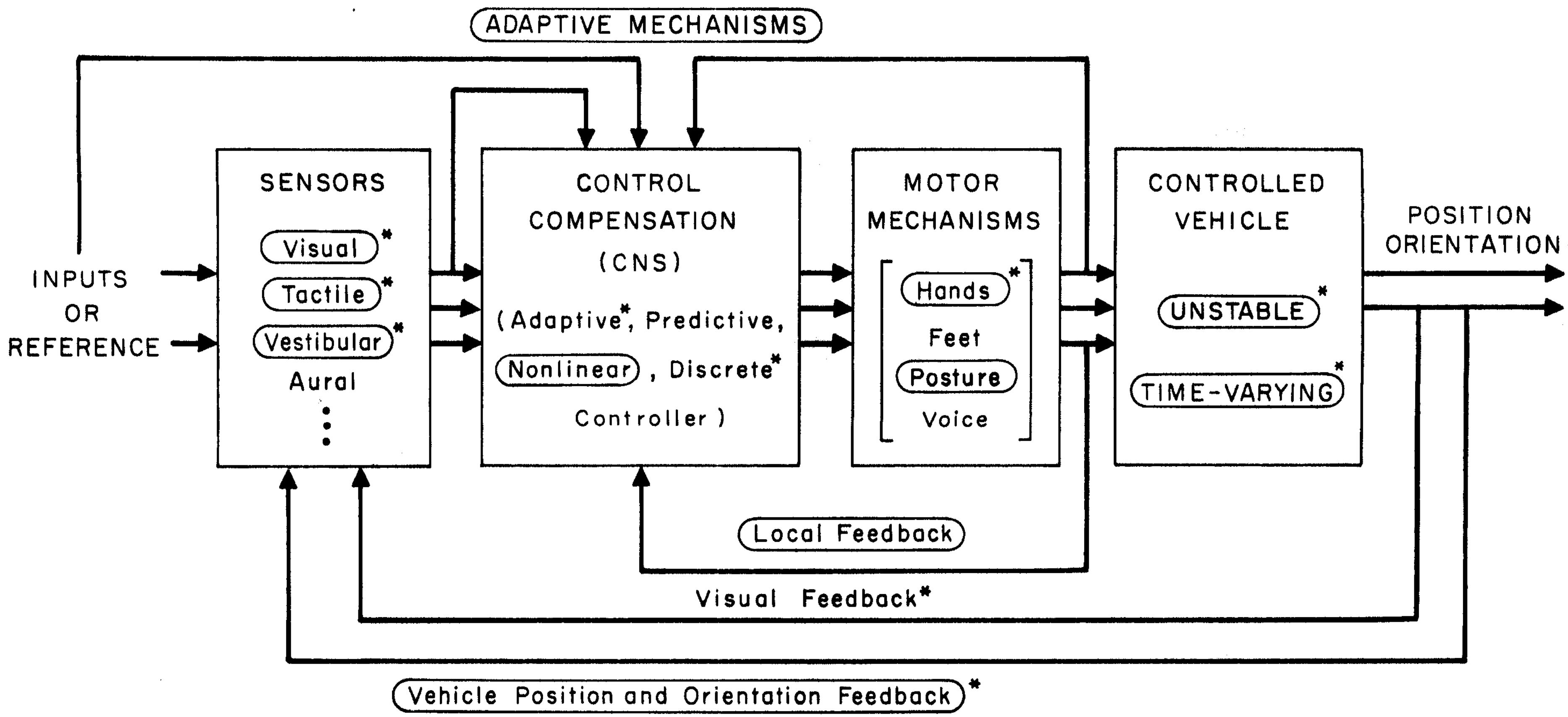

Fig. 1 General Block Diagram of the Man-Vehicle Control Problem
Circles Represent Major Areas Under Research at M.I.T.
Asterisks Represent Areas of Research Jan.-June 1965